Detailed Groundwater Resources Studies in the Rub Al-Khali Desert

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Quality Control and Monitoring of Geophysical (EM) Work for Mapping the Deep Aquifers of the RAK

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Task – 1

GIS Setup & Development including Hardware & Software

Introduction

Over the past decade or so, we developed collective expertise in a number of areas that are relevant to the ongoing integrated hydrological studies/activities in the Rub Al Khali. In this proposal, we list one of these activities pertaining to the set up of a GIS. We propose to develop a web-based GIS to host the Empty Quarter data sets in the Ministry of Water and Electricity, the Water Resources and Studies Division.

Applications of interdisciplinary research in geological, hydrogeological sciences, and related fields often require integration of a number of spatial data sets to enable a better understanding of the relationships between these datasets. We discuss the proposed tasks leading to the development of the web-based GIS, provide a time schedule for the completion of the proposed tasks, and identify the requested funds to enable the implementation of the tasks. We state the expected benefits from having such a data base and cite relevant exercises that we conducted elsewhere.

1- GIS Setup & Development including Hardware & Software

Over the past decade we developed expertise in the general area of geoinformatics with emphasis on applications related to hydrogeology. This area, geoinformatics, is an area that is becoming of increasing importance to geologists. The proposal calls on the creation of the Empty Quarter Geographic Information System (EQGIS) with a web based interface.

Thanks to the advent of GIS technology and its massive potential for data integration, visualization, and modeling, our ability to address and analyze these spatial data sets has dramatically improved. A GIS (Geographic Information Systems) based interface for data archival, manipulation and representation will be adopted. Geographic Information Systems allow for spatial-temporal integration of hydrologic (e.g., water levels, hydraulic conductivities), geochemical (e.g., anions, cations, stable isotopic compositions), geophysical, and remote sensing datasets together with digitized topographic and geologic information, and other spatial datasets (e.g, roads). Because of the immense (hitherto lacking) potential of GIS to display options needed for decision-making and improved project design, the creation of the EQGIS will radically improve our capacity for developing successful, interdisciplinary research and application projects while providing a vehicle for information dissemination via the worldwide web. Specific advantages will include the enhanced spatial analysis of various datasets. Accessible via the World Wide

Web through an Arc IMS web server, the EQGIS will provide an opportunity for researchers to contribute to, analyze, and visualize data from ongoing and completed projects.

1.1. Compilation of the Database

A Microsoft SQL Server will be used as a database engine. The database system will consist of two database servers one at WMU and another at Ministry for Water Affairs. The database servers will be mirrored at the two sites enabling updating and quick access from both countries. The database system will be integrated with ArcIMS (ARC Internet Map Server) using ArcSDE (ARC Spatial Database Engine). ArcSDE is a tool which links spatial data in relational database management systems (SQL Server in our case) to ArcIMS. The latter software is currently widely utilized in the integration of local GIS data sources with Internet data sources for display, query, and analysis using a web browser (Koeppel 2001). Examples of the data sets which will be included are listed below.

1.1.1. Digital map datasets:

This dataset will include geologic maps that were generated by the Saudi Geological Survey. We will first compile relevant existing geologic map data in various formats (e.g., hard copy, digital maps, open file reports, etc). Many of these maps are probably already in a digital form. Additional maps will be digitized/scanned as needed. Digital maps will be re-projected to a common standard projection (e.g., UTM). Geologic map objects will include polygons (e.g., outcrops) and lines (e.g., faults, unconformity). The EQGIS will also incorporate a wide range of thematic maps (maps generated from point data).

1.1.2. Remote sensing dataset

The Earth Sciences Remote Sensing Lab at Western Michigan University has one of the largest collections of satellite data over the Middle East area. Examples of available data sets for the region include Landsat Thematic Mapper (TM), Landsat Multi-spectral Scanner data (MSS), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and SIR-C/X-SAR data. Additional data that will be incorporated in the EQGIS include: Shuttle Radar Topographic Mission (SRTM).

Digital Topography

The Shuttle Radar Topographic Mission data flight (Feb. 11-22, 2000) produced 12 terabytes of raw data currently being calibrated and validated to generate global digital elevation maps. The mission hosted C-band and X-band types of antenna panels. The near-global topographic maps of Earth (Digital Elevation Models or DEMs) are being generated and processed from the C-band data at the Jet Propulsion Laboratory. Interferometry, the acquisition of images for a location from different angles, is used to generate DEMs from SRTM data. Virtually all land surfaces between ± 60^o latitude were mapped by SRTM C-band antenna. Currently, the Earth Sciences Remote Sensing lab at WMU has SRTM data at 90 m resolution. The latter will be incorporated in the EQGIS. The digital elevation data have wide applications in hydrogeology including delineation of stream networks and watershed boundaries, and development of surface runoff and ground water flow models.

SIR-C

SIR-C/X-SAR data contain L-band (wavelength = 24 cm); C-band (wavelength = 6 cm); and X-band (wavelength = 3 cm). L- and C-bands contain both like- and cross-polarization. The tone and texture of the SIR-C/X-SAR images are due to differences in back-scattering of radar waves due to varying surface roughness and relief. The radar waves proved to be a valuable tool for penetrating the dry sand in Egypt and for providing inferences regarding the physical properties of the underlying sand (e.g., McCauley et al., 1982). The Earth Sciences Remote Sensing Lab at WMU has the entire collection of SIR-C/XSAR data over the Middle East. The latter for the Empty Quarter will be hosted in the EQGIS.

TRMM precipitation data

The Tropical Rain Measuring Mission (TRMM) is now enabling acquisition of 3-hourly rainfall data on global scales. TRMM is providing some of the first spaceborne rain radar and microwave radiometric data that measures the vertical distribution of precipitation over the tropics in a band between 35 degrees north and south latitudes. This new data set is helping to resolve major obstacles related to the paucity of rainfall gauge data over the majority of the Earth's surfaces when it comes to the development of meaningful rainfall-runoff models. Our group has now developed robust methodologies (Milewski et al., 2009) to extract spatial and temporal precipitation data over specific time spans for watersheds of interest on regional and global scales. The 3-hourly TRMM precipitation data will be extracted for the Empty Quarter throughout the entire operation time of the TRMM mission (1998-present) and will be included in the web-based GIS.

Spectral reflectance data

Archival remote sensing data acquired from various sensors will be utilized in our analysis. These include: Landsat MSS, Landsat TM, ASTER, and CORONA images. The TM and MSS images each cover an area of 185 km x 185 km with a spatial resolution of 30 m and 79m, respectively. LANDSAT TM (six of seven bands) and MSS (four bands) detect reflected spectral radiation in the visible and near-infrared wavelength region (TM 0.4–2.5 µm; MSS 0.5–1.1 µm). False color composite mosaic of Landsat TM scenes bands 2,4,7 over the the entire Egyptian terrirory. Similar digital products from the individual bands and from band ratio images (e.g., Sultan et al., 1986; 1987) will be included in the EGD. Such products portray compositional information contained in multi-spectral data and are widely used in lithologic and structural mapping (e.g. Arvidson and Sultan, 1990; Arvidson et al., 1993; Abdelsalam et al. 2000; Ramadan et al., 2001; Sultan et al. 2002).

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) was launched in December 1999. It has three separate optical subsystems that collect reflectance and emission data across a 60 km swath: the visible and near-infrared (VNIR) radiometer, short-wave-infrared (SWIR) radiometer, and thermal infrared (TIR) radiometer (Yamaguchi et al., 1996; Wright et al., 1999; Smailbegovic et al., 2000). There are three spectral bands in the VNIR, six bands in SWIR, and five bands in the TIR regions, with 15, 30, and 90 meters ground resolution, respectively. The incorporation of the ASTER data in the EQGIS with its relatively large number of bands (14) and the longer wavelength regions (VIR 0.520-0.860, SWIR 1.600-2.430 and TIR 8.125-11.650 micrometer) will allow mapping of a wide range of compositions that are not readily recognized from the TM data.

1.1.3. Geochemical and geochronologic datasets for groundwater samples

These will include cations, anions, Ph, radiometric ages (e.g., C-14, Chl-36, Kr-81), and trace element abundances, and abundances of key radioactive and stable isotopes for groundwater samples from the Empty Quarter. Geochemical and isotopic data will be extracted from published refereed journals and the Ministry data sets. This data set will be instrumental in advancing research pertaining to origin and evolution of groundwater and water quality.

1.1.4 Field data

Various parameters pertaining to the hydraulic properties of reservoirs will be included in the EQGIS. Examples of such data include depth to water table, hydraulic conductivities and transmissivities, well data (e.g., lithologic logs, total depth, perforation depth, etc). This data is essential for the construction of groundwater flow models and for the analysis of geochemical and isotopic data.

1.1.5. Geophysical data sets

A number of geophysical data sets that are relevant to groundwater exploration will be included. Examples of these data sets and their potential applications in hydrologic investigations include regional and gravity data (e.g., Bouguer anomaly data) and local gravity data to decipher sediment thicknesses, aeromagnetic data to assist in the determination of the depth to the basement and for the delineation of large-scale structures (e.g., Najd faults), Very Low Frequency (VLF) for the identification of sub-vertical conductive layers, Vertical Electric Sounding (VES) for the determination of depth to water table.

1.1.6 Meteorological data sets

All available relevant meteorological data sets will be added to the EQGIS. Examples of these data sets include rainfall, solar radiation, humidity, evapo-transpiration, etc. These data sets are essential for the development and calibration of the rainfall-runoff models and for the calibration of the satellite-based precipitation data.

1.2 Visualization of data sets

The use of ARCIMS software will allow users to conduct a wide range of operations (e.g., pan and zoom, searching for features, querying data, locating addresses, measuring distances, graphically selecting features, printing and saving maps). The generation of a wide range of derivative maps (e.g., buffer zone, contour map) from various map layers (e.g., geologic maps, satellite images) or databases will be enabled. Visualization tools will not be limited to ARCIMS toolboxes. For example, we will utilize the Profile-Maker Tool that would allow users to mix and match databases and create cross sections through various models. Other tools that were developed in house include histograms, transparency tool, etc.

1.4. Expected results, outcomes, and benefits

The following will be accomplished: (1) existing geochemical, remote sensing, and geophysical data, geologic maps, and digital topographic data will be compiled and will be brought to a unified geologic map projection, (2) The datasets will be hosted in a web-based interface allowing access to and retrieval of raw and processed data and metadata, and (3) public domain software for data projection and modeling will be assembled for data representation and visualization.

We see three major advantages for the development of the EQGIS: a) it is cost-effective, maximizing use of existing data and the validity of new data acquisition plans; b) it provides a basis for building models to be tested against the geologic record, and c) it allows researchers, educators, societal agencies, and the general public access to prime data and information, interactive research and project planning tools, published and unpublished interpretations.

1.5. Expertise in the area

We were funded (2005-2008) by the United Nations Developing Program (UNDP) and the Global Environmental Facility to develop cost-effective methodologies for the assessment of groundwater potential in arid lands using the Eastern Desert of Egypt. An integral part of this project entailed the construction of a web-based GIS to host, asrchive, analyze, and distribute all relevant geologic, geochemical, isotopic, field, geophysical, and hydrologic data sets for the purpose of identifying geologic and hydrologic settings that are conducive for the development of groundwater reservoirs (Sultan et al., 2008). The web-based GIS was constructed and now holds over one terabyte of data (http://ims.esrs.wmich.edu/website/eg/viewer.htm). Examples of data sets included in the Eastern Desert GIS include:

(1) Mosaics of geologic maps

(2) Coverage of faults extracted from geologic maps

(3) Mosaics of individual Landsat TM bands 1 through 7

(4) Mosaic of Landsat TM bands 2, 4, and 7

(5) 3 TM band ratio mosaic (5/4x3/4, 5/1, 5/7)

(6) Spaceborne Imaging Radar-C band data (SIR-C)

(7) DEM (Digital Elevation Model) generated from ASTER

(8) Coverage of stream networks derived from DEM data

(9) Watershed boundaries derived from DEM data

(10) TRMM (5 years) precipitation data

(11) Well data (field, geochemical, and isotopic data)

(12) NDVI (Normalized Difference Vegetation Index)

The added value of this technology could be readily demonstrated by the results obtained from the analysis of the spatial and temporal data sets mentioned above in the Egyptian web-based GIS domain. Four types of reservoir were identified in the basement complex of the Red Sea hills, all related to the structural elements of the Najd fault system and over 100 potential well sites were identified (Sultan et al., 2008). The analysis of the Eastern Desert web-based GIS also revealed that deep seated sub-vertical faults act as conduits through which ascending fossil groundwater access to reach shallow alluvial aquifers (Sultan et al., 2007). Similar applications and results pertaining to the origin and distribution of modern and fossil groundwater reservoirs are to be expected if we were to develop the EQGIS. It is noteworthy to mention that our research team at WMU was able to build (remotely) a mirror site in the Egyptian Ministry of Water Resources. This entailed building the Arc-IMS and uploading the digital data sets in it.

Given the success we had with this exercise in the Eastern Desert we are currently funded by NATO to develop a similar project in the Sinai Peninsula and by the USAID to develop a project in the Quetta region in Pakistan. Specifically, we are funded by these two agencies to assess the groundwater potential in these arid areas. We are now expanding the Eastern Desert GIS to include data from the Sinai Peninsula and a web-based GIS is being developed for Quetta (http://ims.esrs.wmich.edu/website/pakistan/viewer.htm).

Examples of additional relevant projects include the development of an interdisciplinary GIS database (TETHYS: http://ims.esrs.wmich.edu/website/tethys/) as a tool for studying plate collision responses in the Tethyan belt. It is predicated on a widely-perceived need for a 'synergistic' approach to developing and testing plate collision models. The database include digitized geological maps, structural indicators, geodetic data, remote sensing data, sample-based major and trace element abundances, radiometric ages, isotopic abundances for ophiolites, ultra-high pressure metamorphic rocks, collision-related magmatic bodies, and seismic data pertaining to mantle and crustal fabric and structure.

Task – 2 : Develop surface-runoff models

1. Introduction

Over the past decade or so, we developed collective expertise in a number of areas that are relevant to the ongoing integrated hydrological studies/activities in the Rub Al Khali. In this proposal, we list one of these activities pertaining to the construction and calibration of a continuous rainfall runoff model for the RAK watershed.

Efforts to understand and to quantify precipitation and its partitioning into runoff evapotranspiration, and recharge are often hampered by the absence or paucity of appropriate monitoring systems. We will apply methodologies for rainfall-runoff and groundwater recharge computations over the RAK that heavily rely on observations extracted from a wide-range of global remote sensing data sets (TRMM, Landsat TM, AVHRR, AMSR-E, and ASTER). A two-fold exercise will be conducted. Spatiotemporal remote sensing data (TRMM, AVHRR and AMSR-E) will be extracted from global data sets over the test sites using RESDEM, the Remote Sensing Data Extraction Model. RESDEM will be also used to identify and to verify precipitation events throughout the past decade (1998-2008). This will be accomplished using an automated cloud detection technique to identify clouds and to monitor their propagation prior to and throughout the identified precipitation events, and by examining changes in soil moisture (extracted from AMSR-E data) following the identification of clouds. A catchment-based, continuous, semi-distributed hydrologic model (Soil Water and Assessment Tool model; SWAT) will be calibrated against observed runoff values and will then be used to provide a continuous simulation (1998-2008) of the overland flow, channel flow, transmission losses, evaporation on bare soils and evapo-transpiration, and groundwater recharge for the major watershed(s) in the RAK. Moreover recharge will be computed for each of the major aquifers in the RAK.

We discuss the methodologies that we developed and were successfully applied in similar terrains in the Sinai Peninsula and in the Eastern Desert of Egypt, provide a time schedule for the completion of the proposed tasks, and identify the requested funds to enable the implementation of the tasks. We state the expected benefits from the development of such a model and cite relevant exercises that we conducted elsewhere.

2. Geology, Hydrogeology, Landforms, and Climate of the RAK

Precambrian crystalline basement of the Arabian Shield crops out along the eastern margins of the Red Sea coastline forming the westernmost margin of the RAK terrain. The basement complex rocks are impermeable and groundwater in basement areas is found in fractures or in the alluvial aquifers within the wadi network dissecting these domains. Unconformably overlying the crystalline basement are thick sequences of sedimentary formations ranging in age from Cambrian to recent; they dip gently to the east and thicken in the same direction reaching thicknesses of up to 5 km in the vicinity of the Persian Gulf. These stratigraphic relationships are demonstrated in Fig. 1, a generalized schematic cross section along a SW to NE trending transect.

Groundwater in the RAK is hosted primarily in sandstone, limestone, and dolomite formations separated by interleaving confining shale units. These aquifers are here grouped in: (1) Paleozoic sandstone aquifers (e.g., Wajid aquifer: 200-900m thick) and limestone and dolomite aquifers of the Kuff formation (250-600m), (2) Mesozoic sandstone aquifer (e.g., Minjur: 400m thick; Biyadh-Wasia: 425m), and (3) Cenozoic (Eocene and Neogene) limestone and dolomite (e.g., Umm er Radhuma: 250-700m; Dammam: 250m) (Al Alawi and Abdulrazzak, 1994; 2001; Ministry for Higher Education, 2000).

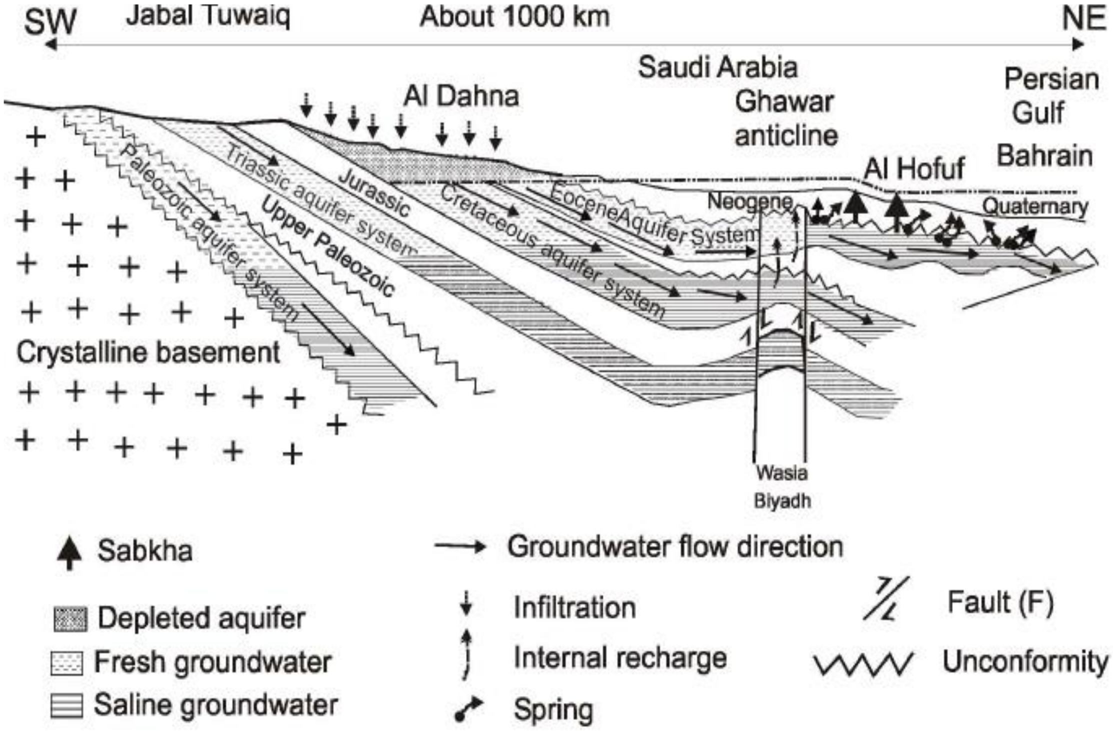

Figure 1. A SW to NE schematic cross section through the RAK modified from Beaumont (1977) and AlSharhan et al. (2001).

These sedimentary formations are exposed in the foothills of the Red Sea Hills providing ample opportunities for groundwater recharge for all aquifers (Cambrian to Quaternary) from rain precipitating over the Red Sea Hills and surroundings. Precipitation is concentrated over the mountain ranges and/or highlands surrounding the area from the east (Red Sea Hills), west (Oman mountains), south (e.g., Hadramount and Dhofar mountains), and north (Yabrin mountains) and is channeled by extensive E-W trending watersheds intercepting the recharge areas. These relationships are demonstrated in Figure 2a, which shows a mosaic of Landsat Thematic Mapper scenes draped over digital elevation data for the RAK and surrounding mountains and a similar drape for the major watersheds and drainage networks in the area (Fig. 2b). The precipitation over the southern and eastern highlands is less likely to recharge the aquifer sequence in its entirety since only the more recent aquifers (Cenozoic) crop out at the foothills of these mountain ranges

Radiocarbon dating of groundwater samples from a number of these reservoirs (Saq: 22,000-28,000 ka; Biyadh-Wasia: 8,000-16,000 ka; Umm er Radhuma: 10,000-28,000 ka) have lead to interpretations suggesting that these reservoirs were recharged during previous wet climatic periods in the Quaternary (AlSharhan, 2003; Beaumont, 1977; Otkun, 1971). Although we believe that the aquifers are largely formed of fossil water, we suggest that during the intervening dry periods, as is the case now, these aquifers must receive additional recharge given the relatively high precipitation over the Red Sea Hills and the presence of a network of ephemeral streams that can channel these waters to the recharge areas at the foothills of these mountains. This has been demonstrated to be the case in similar settings in the Eastern Desert of Egypt and the Sinai Peninsula (Sultan et al., 2007; 2000).

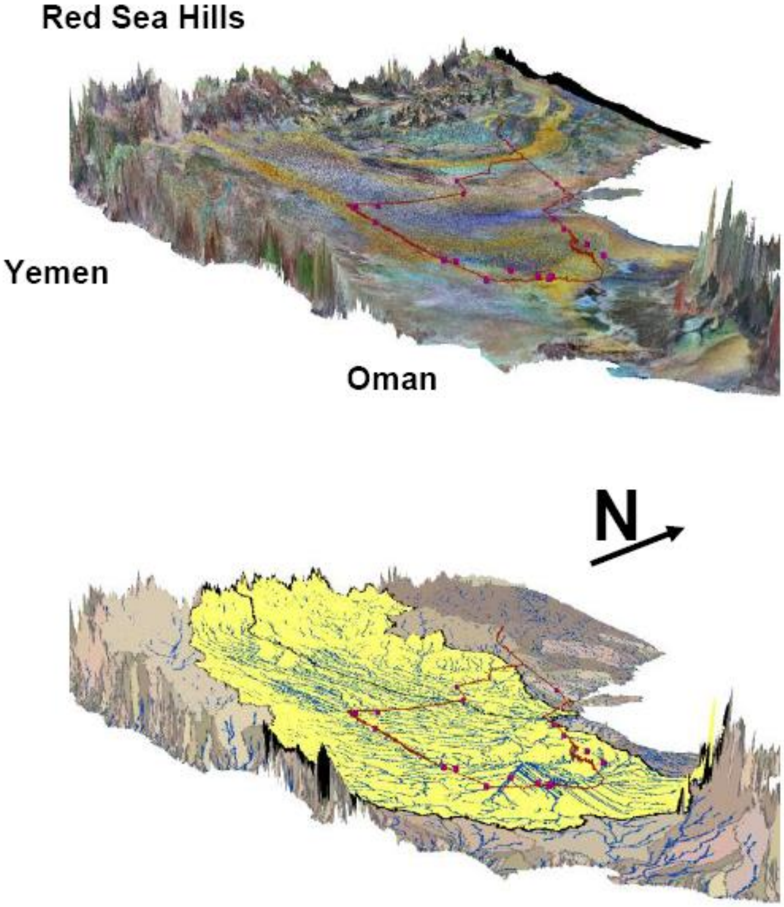

Figure 2 - representations. (a) Landsat TM false color images draped over vertically exaggerated digital elevation data (1 km SRTM). (b) Watersheds and drainage networks extracted from SRTM data draped over 1 km SRTM data. Also shown on Figs. 2a and 2b are our sample locations (red

3. Methodology

The adopted approach has three main steps. Firstly, we collect and pre-process relevant remote sensing data. Secondly, we identify and verify using multiple remote sensing datasets the relatively larger precipitation events that are more likely to produce runoff and recharge. Following the identification of rainfall events, we verify the validity of the identified precipitation events using several remote sensing techniques. Thirdly, we adopt a catchment-based, continuous, hydrologic model to quantify the spatial and temporal distribution of surface runoff and potential groundwater recharge. Three types of remote sensing datasets will be collected and processed over the same time period (1998 - 2008) to enable the extraction of realistic spatial and temporal distribution of rainfall over the RAK. These include: (1) TRMM data that provides global (50°N-50°S) data on rainfall using microwave and visible-infrared sensors every three hours with a 0.25º x 0.25º footprint, (2) Advanced Very High Resolution Radiometer (AVHRR) data with a spatial resolution of 1.1 km to be used for verifying precipitation events through cloud detection, and (3) Advanced Microwave Scanning Radiometer (AMSR-E) with a footprint of 0.25º x 0.25º, to be used to extract soil moisture content taking advantage of the large differences in dielectric constants of wet and dry soils. A fourth type of remote sensing data set, the Shuttle Radar Topographic Mission (SRTM) will be used to extract digital elevation for the study area.

3.1. Collection and pre-processing of relevant remote sensing data

The pre-processing step for the large temporal remote sensing data sets (TRMM, AVHRR, AMSR-E) will be enabled using a recently developed module, the Remote Sensing Data Extraction Model (RESDEM), that was developed using an Interactive Data Language (IDL) code (Milewski et al., 2009a). RESDEM allows: (1) extraction of subsets of remote sensing data sets over user-defined spatial and temporal domains, and (2) processing of the images to bring each of the data sources to a common projection and to eliminate spectral variations (within and between scenes) related to differences in sun angle elevations. Applying user defined functions (e.g., area, duration), global remote sensing data sets (TRMM, AVHRR, AMSR-E) will be subset to cover the selected area and the time period (1998-2008) of interest.

An additional parameter (threshold value) will be applied to refine the TRMM subset data to include only the events exceeding a selected threshold value. Since the “smaller” precipitation events are unlikely to produce significant runoff and groundwater recharge, we will omitt events that fall short of our pre-determined precipitation threshold value of 5 mm, the minimum amount of precipitation that was found to produce runoff in any of the examined watersheds. By adopting such procedures, we will minimize the labor involved in the generation and inspection of the verification products cited in this section.

The selected events, the ones exceeding the threshold value will then be verified within the RESDEM domain using a module (cloud detection module: CDM) that tests for the presence of clouds and another (soil moisture module: SMM) that tests for changes in soil moisture for precipitation events (Milewski et al., 2009a). Next, we describe in detail our reasoning for the selection of our preferred TRMM precipitation dataset (3B42.v6), sources of error in this data and methodologies adopted to correct these errors, and finally procedures for the extraction and verification of precipitation events from a suite of satellite data. RESDEM was used to accomplish the extraction and verification steps (Milewski et al., 2009a).

3.2. Identification and verification of identified rainfall events

Four types (3B42.v5, 3B43.v5, 3B42.v6, 3B43.v6) of TRMM data are available for users. The 3B4X.v5 products are earlier versions of the 3-hourly TRMM products, whereas the 3B43.vX is a monthly product. The 3-hourly 3B42.v6 TRMM dataset was selected for our analyses because it has lower false alarm rates (FAR), higher probability of detection (POD) rates during dry periods, and an overall greater critical success index (CSI) compared to the other products (Chokngamwong and Chiu, 2006; Schaefer, 1990).

One should not expect a 1:1 correspondence between the TRMM and rain gauge data sets given the fact that the rain gauges provide local measurements, whereas the TRMM integrate observations over much larger domains (covered area: 0.25° x 0.25°). It has been also demonstrated that the TRMM sensor can misidentify a variety of Earth surfaces for precipitating clouds (e.g., Bauer et al., 2002) giving a false indication for light rainfall (<0.5mm/hr) (Turk et al., 2003). Because TRMM measurements are acquired every three hours, short events that start and end in between two consecutive TRMM acquisitions can go undetected as well. Thus, there is a tendency for satellite-based rainfall to underestimate event-based precipitation especially in arid areas where precipitation events tend to be short and intense (Morrissey and Janowiak, 1996). Earlier findings of Chiu et al., (2006) and Chokngamwong and Chiu, (2006) showed that TRMM in arid environments could underestimate precipitation by 15 to 30%. Next, we describe the procedures we will adopt to address these two potential sources of error.

To correct for the fact that the TRMM is apparently underestimating precipitation in the study area, the TRMM datasets will be calibrated by multiplying the TRMM data by a factor to bring the TRMM values to match those observed at the rain gauges. False positives will be addressed as well. We will verify the major precipitation events (inferred from TRMM) by conducting the following steps: (1) applying automated methods to detect the presence of clouds in processed temporal AVHRR scenes acquired before (up to 2 days) and throughout the examined precipitation events and, 2) visual inspection of soil moisture difference images to detect an increase in soil moisture. The latter will be derived from pairs of AMSR-E images, an image acquired before (1-4 days) and another (1-4 days) after the investigated event. We will use the VUA-NASA Land Surface Parameter Model which utilizes passive microwave remote sensing approaches to retrieve soil moisture from observed brightness temperatures (Wagner et al., 2007). Microwave observations are sensitive to soil moisture content due to the large differences in dielectric constant values for wet (~80) and dry soils (<4)(Njoku and Kong, 1977).

A precipitation event will be considered as being verified if substantial cloud coverage and change in soil moisture was associated with the investigated event; events that do not meet these criteria will be omitted.

3.3 Model Construction

The SWAT model provides a continuous simulation of the overland flow, channel flow, transmission losses, evaporation on bare soils and evapotranspiration on vegetated canopy, and potential recharge to the shallow alluvial aquifers (Arnold and Fohrer, 2005; Arnold et al., 1998). SWAT was selected because it is a continuous model, allowing rainfall-runoff and groundwater-recharge estimates to be made over extended periods of time and it is compatible with GIS data formats allowing us to import the existing GIS databases for the RAK into the model.

3.3.1 Database Generation using GIS

The initial step in the development of our hydrologic model will be the generation of a database incorporating digital mosaics from various sources. Recently released GIS-based SWAT modules (ArcSWAT: SWAT, 2007) can readily display and query geospatial information in a GIS environment and use GIS databases as inputs to the SWAT model. We will generate the following digital mosaics covering the entire RAK that will be used as model inputs: (1) temporal, calibrated rainfall data (3-hourly precipitation data: 1998-2007) extracted from TRMM, (2) a mosaic from geologic maps each covering 2° latitude by 3° longitude (scale 1:500,000), (3) landuse maps extracted from the USGS 1 km global Land Use and Land Cover database generated from AVHRR data (acquisition date: April 1992-March 1993) (Anderson et al., 1976) data that is being used for a wide range of environmental and modeling applications (e.g., Loveland et al., 2000), (4) a mosaic of quadrants (each covering 5° by 6°) from the NASA Landsat GeoCover Dataset 2000 (Landsat GeoCover Orthorectified Thematic Mapper Dataset 2000; spatial resolution: 15m) (Tucker et al., 2004), (5) climatic parameters including solar radiation, wind speed, air temperature, and relative humidity and (6) digital elevation model mosaic from the SRTM scenes at 90 m resolution. The data sets described above, come in various projections, will be co-registered to a reference map (NASA Landsat GeoCover Dataset 2000) and re-projected to a common projection (UTM, WGS84).

Using the extracted DEM, the Topographic Parameterization (TOPAZ) program will be then applied to identify water accumulation patterns, distribution of watersheds, stream networks, as well as geometric properties (areas, slope, lengths, etc.) for the main basins and valleys (Garbrecht and Martz, 1995). The geology mosaic will be used to identify and map soil types and the Landsat Thematic Mapper (TM) mosaic will be used to validate and refine the DEM-based distribution for watersheds and stream networks. Average monthly climatic data (e.g., minimum temperature, maximum temperature, solar radiation, and wind speed) will be extracted from the Global Historical Climatology Network (GHCN) global climatic dataset (EarthInfo, 1998-2005).

3.3.2 SWAT Model Setup

The hydrologic model of the RAK will be constructed within the SWAT framework to simulate the hydrologic processes using its physically-based formulations. Watersheds will be divided into subbasins and subbasins will be further subdivided into hydrologic response units (HRUs) with each HRU possessing unique land use and soil type attributes. Water partition and balance in each HRU will be calculated; flows from all HRUs will be summed for each subbasin and routed through channel networks to subbasin outlets and ultimately to the watershed outlet.

Initial losses and direct overland flows in HRUs will be estimated using the U.S. Department of Agriculture's - Soil Conservation Service method (SCS, 1972). The SCS method was successfully applied to ephemeral watersheds in southwestern United States, areas that bear resemblances in their climatic, hydrologic, topographic, landscape, and soil and landuse types to those in the RAK. The bulk of the physical properties of the HRUs in each sub-catchment will be extracted from existing databases or ones that will be generated for soils, land cover, and land use types throughout. Initial losses are largely dictated by the curve numbers (CN); the latter is a function of the antecedent moisture condition (AMC), the land use, the hydrologic condition, and the hydrologic soil type (SCS, 1985).

Initial losses will be assumed to enter the soil profile after interception of canopy storage; losses will then be routed using a soil-water storage/routing method adopted in SWAT that partitions initial losses through processes including transpiration, soil water evaporation, infiltration, lateral flow, and groundwater recharge. Evaporation on bare soils and transpiration on vegetated canopy will be calculated using the Penman-Monteith method (Monteith, 1981). Water exceeding soil field capacity throughout the soil profile will be routed to the shallow aquifer at each time step and partitioning from the latter to the deep aquifer will be assumed to be negligible (Scanlon, 1994). A simplified top soil profile will be employed in the model with soil properties dictated by the assigned land use and soil type.

Channel flows will be estimated using the Muskingum routing method (McCarthy, 1938), whereby the Manning's coefficient for uniform flow in a channel will be used to calculate the rate and velocity of flow in a reach segment for a given time step. Channel flows are subject to transmission losses, a partitioning that depends on the channel geometry, upstream flow volume, duration of flow, bed material size, sediment load, and temperature (Neitsch et al., 2005). We will assume negligible losses from channel flows to transpiration or evaporation for the following reasons: (1) vegetation is scarce or absent under the prevailing arid to hyper-arid conditions, (2) flows are short-lived, typically not lasting for more than a day with cloudy conditions typically prevailing throughout storm events, and (3) alluvial deposits flooring the valleys have high hydraulic conductivities.

Simulations will be performed at daily time steps, the smallest time steps allowed by SWAT using cumulative 3-hourly TRMM data over periods of 24 hours and applying monthly average values for temperature, wind speed, relative humidity, and solar radiation as daily estimates.

3.3.3 SWAT Model Calibration

Simulation using the process-based SWAT model to estimate hydrologic response involves calibration of some forty parameters. Calibration will involve: (1) parameter specification using sensitivity analysis, (2) initial parameter estimation, and (3) final automatic calibration.

Parameter Specification

Automatic calibration processes often become time consuming and less practical with increasing number of parameters to be calibrated. An attempt will be made to reduce the number of parameters to be calibrated by identifying the most sensitive of these parameters, the ones that had the largest influence on predicted runoff. Sensitivity analysis will be conducted using the LH-OAT method; parameters will be varied to assess the corresponding level of change in outputs. The LH-OAT method combines the Latin Hypercube (LH) sampling method (McKay, 1988; McKay et al., 1979) with the One-factor-At-a-Time (OAT) method (Morris, 1991). LH sampling will be used to generate input data for each parameter set from the assigned distributions and ranges. The LH simulation performs random sampling functions similar to those described by Monte Carlo simulations, but applies simplified sampling routines which significantly reduce the number of simulation runs (Van Griensven et al., 2006). Using the OAT method, the impacts of changes of individual parameters on model outputs will be evaluated. Throughout the sensitivity analysis, attempts will be made to match to a first order modeled runoff with observed stream flow data collected for the various stream flow gauges. Initial parameter values and ranges will be largely extracted from SWAT databases and will be guided by reported and/or expected values for arid and semiarid environments. The selected parameters (outputs of sensitivity analysis) will then be used for model calibration; these parameters largely control processes of overland flow, interception, soil storage/routing, channel routing, and groundwater recharge.

Parameters Estimation

Following the identification of the most sensitive parameters, manual calibrations will be conducted to estimate inputs for the automatic calibration step, namely the initial values. In conducting these calibrations, one parameter will be adjusted at a time to match modeled average annual watershed runoff against existing stream flow observation data. Adjustments will then be applied to these values throughout the adopted manual calibrations. Manual calibrations will be applied to the most sensitive of the selected parameters. For the remaining less sensitive parameters, that have a lesser impact on modeled runoff, we will adopt reported values for these parameters that were applied to areas with similar climatic and hydrologic settings.

Automatic Calibration

An automatic calibration will be performed to further refine the model parameters extracted from the initial manual calibration. This calibration uses a multiplier for each parameter to adjust the parameter while retaining the relative spatial pattern generated in data-processing module for all sub-basins. The shuffled complex evolution method (SCE) (Duan, 1991; Sorooshian et al., 1993) implemented in SWAT (Van Griensven,

2002) will be used to calibrate the parameter multiplier. The SCE algorithm will be used to conduct a global probabilistic search for multiplier values for the entire watershed. The parameters for each sub-basins will be scaled up or down by the derived multiplier. The objective function used in the automatic calibration will be utilized to minimize the mean square error between observed and simulated stream discharge. The coefficient of determination (R^2) and the coefficient of efficiency (COE)(Nash and Sutcliffe, (1970) will be used to evaluate the correspondence between observed and modeled discharge.

4. Expected results, outcomes, and benefits

The following will be accomplished:

(1) A digital database incorporating co-registered digital mosaics including:
  - temporal, calibrated rainfall data (3-hourly precipitation data: 1998-2008) extracted from TRMM;
  - a mosaic extracted from geologic maps (scale: 1:500,000);
  - a mosaic of landuse maps extracted from the USGS 1 km global Land Use and Land Cover database;
  - a mosaic of Landsat TM quadrants (each covering 5^o by 6^o) extracted from the NASA Landsat GeoCover Dataset 2000;
  - climatic parameters including solar radiation, wind speed, air temperature, and relative humidity;
  - digital elevation model mosaic from the SRTM scenes at 90 m resolution. The data sets described above, come in various projections, will be co-registered to a reference map (NASA Landsat GeoCover Dataset 2000) and re-projected to a common projection (UTM, WGS84).

(2) A physically-based rainfall-runoff SWAT model constructed for the RAK and calibrated through processes involving parameter specification, estimation, and automatic calibration.

(3) Reliable estimates for average annual amount of precipitation, surface runoff, initial losses (e.g., infiltration-evaporation), transmission losses, and shallow aquifer recharge throughout the investigated period (1998-2008)

(4) Training the Saudi scientists on modeling and technology transfer through a series of short courses on the subject

5. Expertise in the area

We have conducted a preliminary integrated (geochemistry, remote sensing, GIS) study aimed at deciphering the origin and history of the groundwater in the RAK that was recently published in the Journal of Hydrology (Sultan et al., 2008). Figures 2a and 2b show the traverse along which groundwater samples were collected for isotopic and geochemical analyses. Preliminary analysis of 3-hourly TRMM (1998-2005) precipitation data and digital elevation data shows that approximately 27% of the average annual precipitation (150 x $10^9 m^3$) over the Arabian Peninsula is channeled toward the recharge zone of the RAK aquifer system, of which an estimated 4 x 10^9 m^3 a^{-1} to 10 x 10^9 m^3 a^{-1} of this water is partitioned as recharge to the RAK aquifer system. Additional detailed integrated studies proposed here on recharge rates, sustainability, and water quality issues for the RAK aquifers could demonstrate that the RAK is one of the most promising sites for groundwater exploration in the Arabian Peninsula. Results highlight the importance of investigating the potential for sustainable exploitation of the RAK aquifer system that was largely recharged in previous wet climatic periods yet is apparently still receiving modest modern meteoric contributions.

The RESDEM module to be used in the proposed study for the RAK was developed by our research team at the Earth Sciences Remote Sensing Lab and is now being used for the extraction, validation, and processing of public domain remote sensing data sets over areas and time spans of interest. RESDEM processes and applications were described in detail in an article that will be coming out soon in the Journal of Computers in Geosciences (Milewski et al., 2009a). Using funding from NSF, UNDP, and NATO, we developed RESDEM together with the Rainfall-runoff modeling methodologies described in the proposal and applied these methodologies to assess the groundwater potential in arid lands in the Eastern Desert and the Sinai Peninsula in Egypt. The rainfall-runoff modeling results for the Eastern Desert and the Sinai Peninsula were summarized in a recent article (Milewski et al., 2009b) that is coming out shortly in the Journal of Hydrology. For the investigated watersheds in the Sinai Peninsula, the average annual precipitation, average annual runoff, and average annual recharge through transmission losses were found to be: 2,955 x $10^6 m^3$, 508 x $10^6 m^3$ (17.1% total precipitation (TP)), and 463 x $10^6 m^3$ (15.7% TP), respectively, whereas in the Eastern Desert these values are: 807 x $10^6 m^3$, 77.8 x $10^6 m^3$ (9.6% TP), and 171 x $10^6 m^3$ (21.2% TP), respectively. Results demonstrated the enhanced opportunities for groundwater development in the Sinai Peninsula (compared to the Eastern Desert) and highlight the potential for applications in hydrologically and climatically similar terrains in the Rub Al Khali (RAK).

Task 3 :

Mathematical Model Development and Applications to the RAK

1. Introduction

The main goal of this study is the assessment and evaluation of the groundwater potential of the Rub' Al Khali desert by applying several scientific and technical tools, including the development of mathematical models of groundwater flow in the existing aquifers in the area. This mathematical model will allow to a better understanding of the hydrogeological systems and their functioning, in addition to quantify the various flow components of the water balance.

Over the past decade or so, we developed expertises in a number of areas that are relevant to integrated hydrological and hydrogeological studies/activities in different regions, where the model development is the key point that helped to determine the groundwater resources potential, especially for future planning and sustainable development management purposes. In this proposal, we list relevant activities pertaining to the design of the mathematical model for the RAK aquifer system: conceptualization, construction, calibration, verification and management.

We discuss the standard methodologies that we developed and were successfully applied in various areas and still valid also for the RAK study, provide a time schedule for the completion of the proposed tasks, and identify the requested funds to enable the implementation of the tasks.

2. Model design

The adopted approach has several steps: Concept development, the numerical code/software to be used, Model geometry, boundary conditions and hydrodynamic parameters, stresses upon the groundwater system, calibration, sensitivity analysis and prediction within the time of applied scenarios fixed by the Ministry. Firstly, we review all available data/models and publications to include new information not yet available in the existing models. We collect and pre-process all data, including those to extent the whole catchment area of the studied aquifers within the RAK.

2.1. Conceptual hydrogeological model

The conceptual model step is the most important, since it requires a thorough understanding of hydrogeology, hydrology and dynamics of groundwater flow in and around the studied area of the RAK. Most of the geological and hydrogeological input can be processed from the GIS and data base to be developed and updated by the new data collected and/or generated within this study, such as new hydrogeological maps and cross sections. Based on previous studies, the major aquifers in the RAK area are Wajid, Wasia-Biyadh, Aruma, Umm Er Radhuma, Dammam and Neogene aquifers. The top and bottom of these aquifers, in addition to their extension must be well known.

2.2. Model Geometry and grid size

The model geometry will be defined based on the base maps, model boundaries, cross sections. This will define the shape and the size of the model. The grid size (for cells or elements) will be discussed with the Ministry to define the model accuracy, especially close to the existing wells and/or projected wells and should be compatible to the existing groundwater models.

2.3 Model parameters

Those refer to the hydrogeological characteristics, such as hydraulic conductivities, transmissivities, storage parameters and effective porosities. Most of them can be found in the pumping test results from previous or current studies. The parameter distribution and space variability, under maps, is very important to show areas and zones of better well implantation for different aquifers. The time stepping during transient simulations will be adequately selected and will be discussed as well as the grid size for the spatial scaling. The numerical code to be used will be selected in collaboration and approval of the Ministry. The standard code frequently used is MODFLOW with its pre-and post processors platform; and is able to perform all the required simulations for groundwater flow in different complex situations. However, other numerical codes are also available based on other techniques, but MODFLOW has the advantage to be simple and user friendly compared to other codes in terms of the theory behind, applied techniques and user friendly (pre-post processors to handle input and to visualize output) and its success to handle several field works. It is also compatible with some GIS data formats (GMS, for instance) allowing us to import the existing GIS databases for the RAK into the model.

2.4 Boundary conditions, stresses and initial conditions

This step will assign and describe boundary and initial conditions for transient simulations. The input will be extracted from the data base and GIS developed in this study, especially from available piezometric maps and historical records of observation wells. The stresses are generally the withdrawals, recharge, irrigation and other forces acting upon the aquifers that must be assigned correctly to the model as input, in addition to model parameters and other specific parameters linked to numerical solvers and techniques before running the model. All these input can be facilitated by the use of the code pre-processors in importing data from the available GIS and data base. These input will be generated under the form of maps to help in translating the available hydrogeological knowledge into the model.

2.5 Model run, calibration and sensitivity analysis

After assigning all the data and aquifer parameters into the model, the RAK model will be run and the results of the head distribution of each aquifer will be analyzed and compared to the selected references and available records until the model is calibrated. The process is based on adapting the distribution of K-values for steady state simulations and S-values for transient conditions. Both, trial-and-error and automated calibrations will be used. Maps of head distribution, calibrated K-values and S-values will be produced and discussed. A sensitivity study will be also performed for the model to analyze the effects of parameter variability on the simulation results. The results of the calibrated model in both steady state and transient conditions will be discussed, especially more understanding of the hydrogeological system and its functioning will be gained from the model results.

Based on the model results, water balance in steady state and transient conditions for aquifers will be calculated and commented.

2.6 Prediction for planning scenarios and water resources development

Once the model is calibrated for both steady state and transient conditions, it can be used for prediction of planning scenarios fixed by the managers to support the design of their groundwater development program within the time and space. All these runs will be performed in consultation with the Ministry of water and electricity. Selection of optimum exploitation from aquifers will be also accomplished.

3.Summary of the results and deliverables

The following will be accomplished:

(5) A Conceptual model for the RAK area which incorporates all the input data
(6) A calibrated RAK model in steady state with maps and water balance
(7) A calibrated model in transient conditions with maps, piezometric records and water balance
(8) Prediction model for planning future scenarios in consultation with the Ministry
(9) Trainings the Saudi scientists on modeling and technology transfer through a series of short courses on the modeling techniques, model design, calibration and applications

4. Expertise in the area of modeling

In the past, we have conducted several modeling studies, including data collection, input, conceptual model, model calibration in both steady state and transient conditions and prediction scenarios for water resources development program in various regions in Morocco, Mediterranean countries and Europe. Thanks to our team, we Have been awarded in 2006 the International Prize Sultan bin Abdulaziz for Water in Groundwater section.

The team conducts research on Hydrology, groundwater modelling of flow and pollutant transport in porous media and heterogeneous and complex aquifer systems; with direct applications on hydrogeology and environmental pollution. These include groundwater management for supplying population and irrigation areas; Monitoring, Modelling, Optimisation and Management, especially in the Mediterranean region (Morocco, Tunisia, Spain, Italy and Palestine). Applied research is covering hydrogeological characterisation of groundwater systems at the large scale and their interaction with surface water, modelling and pollutant transfer in soils and groundwater and their impacts on the natural environment. These research works are conducted in the framework of **national and international research programmes (consulting and applied research contracts)** such as the EU-Brussels, FAO-Rome, UNESCO, bilateral agreements (France, Spain, Italy, Belgium, USA (NSF) and Tunisia). Concerning Field work studies on Hydrogeology and water resources management and strategies in Morocco, several aquifers have been studied in the framework of theses of Engineering (Groundwater section at EMI), theses of MSc or in the preparation of the PhD in Applied Sciences and Engineering, in addition to consulting and research contracts made in the framework of national and international contracts with several organisms, including the Hydraulic department, Ministry of Water and Environment (SEEE), the National Office of Potable Water (ONEP), and the regional water basin agencies.

Based on previous and recent studies, the RAK aquifer system could demonstrate that it is one of the most promising sites for groundwater exploration in the Arabian Peninsula. Results highlight the importance of investigating the potential for sustainable exploitation of the RAK aquifer system that was largely recharged in previous wet climatic periods yet is apparently still receiving modest modern meteoric contributions. The design of the RAK model could estimate the water resources potential and suggests the best way a sustainable management of the aquifers. The methodology used for previous studies could be also used for the RAK area, since it is universal.

Task : 4

Quality Control and Monitoring of Geophysical (EM) Work For Mapping the Deep Aquifers of the Rub Al Khali

Executive Summary

This proposal addresses the issue of monitoring and controlling deep-looking EM (ElectroMagnetic) geophysical work assumed to be carried out by a yet-to-be identified Prime Contractor, for the purpose of mapping deep aquifers in the Rub al Khali (RAK) of Saudi Arabia.

These deep aquifers in the RAK will be referred to hereafter as the RAKAS (RAK aquifer system). The geophysical work would be part of a much larger program, including geology, GIS, hydrogeology, flow measurements, etc.

During the project, Saudi geoscientists at KSU (King Saud University, Riyadh) and possibly other organizations which may be involved will develop significant competence in theoretical and applied aspects of deep EM exploration, and progressively assume increasing responsibility for the work.

It is assumed that the work program of the Prime Contractor will be a major multi-year program to map and characterize these aquifers. This program will obviously be mainly hydrogeological in focus, but will necessarily include ***deep-penetrating*** EM (electromagnetic) geophysical technique(s). EM techniques are sensitive to electrical conductivity. Most aquifers are more electrically conductive than the formations above and below the aquifers.

EM techniques are characterized as either "natural source" (no man-made energy source required) or "Controlled Source" (CSEM) which require a man-made power source. The usual EM techniques applied to groundwater exploration and characterization include the controlled-source techniques VES (Vertical Electric Sounding"), dipole-dipole resistivity, TDEM (Time Domain EM), and Frequency Domain EM.

However, all of these are shallow-penetrating techniques. VES and resistivity require the use of a transmitter/motor generator and fuel supply, and also, well-grounded current electrodes (which may be difficult to achieve in the extremely dry surface sands).

VES and dipole-dipole resistivity (with typical multi-channel systems) have considerable difficulty seeing below the first conductive layer. VES requires very large current dipoles (expanding up to several km in length) to achieve significant depth of exploration.

TDEM and FDEM do not require grounded electrodes, but typical groundwater-oriented FDEM has depth of investigation of usually < 100m, and TDEM, < 300m. As well, TDEM has difficulty seeing through the first conductive layer.

The depths in the RAKAS exceed the capabilities of the usual techniques described above, so to investigate the aquifer formations below the shallowest one, deep-penetrating EM technique(s) are required. The only two CSEM options are CSAMT and LoTEM. The details of these techniques are not discussed here, for the reason in the following paragraph.

Any deep-penetrating CSEM technique requires a powerful motor generator, with ample fuel supply, and a large transmitting antenna. The logistic handicap of CSEM for RAK operations is obvious.

Therefore, the most feasible EM technique to use in this project appears to be MT (Magneto-tellurics), a well-known natural-source geophysical technique (invented in the 1950s) used in exploration for hydrocarbons, geothermal systems, metallic minerals, and groundwater. The reader can easily locate good MT tutorials on the internet.

The MT signal source is natural fluctuations of Earth's magnetic field. Since no heavy motor generator / fuel supply /large antenna is needed, this greatly simplifies operations in the RAK.

MT depth of investigation is >tens of km, which is more than sufficient for this project.

MT equipment is relatively compact and light in weight, battery powered, with small footprint and minimal environmental disturbance; and MT provides a rich information set, with dimensionality indicators, etc.

Note that MT fieldwork has already been carried out in Saudi Arabia for hydrocarbon exploration (Stewart et al, 1996; Al-Dulaijan et al 2008) so there is no doubt that the technique can be applied in the Saudi environment. Special equipment (electric field preamplifiers) may be used as required to mitigate the problem of highly resistive surface (dry sand).

YEAR 1

Before any field work is undertaken in an environment as challenging as the RAK, it is advisable to review existing relevant data, and to carry out a modeling program to gain insight into the detectability, resolution and signature of the various aquifers at various locations.

The most relevant information used in MT modeling experiments is the electrical resistivity and thickness of the modeled formations. As per (Sultan et al, 2008)

ARAMCO has drilled >150 exploration wells in the RAK. (Another source indicates that some of these wells were drilled by MoWE). Probably the ARAMCO wells (at least) are logged. The suite of logs probably includes resistivity. Additional well information probably includes the stratigraphic section of the wells (with depths and thicknesses). Note the depth information derived from the ARAMCO wells, as presented in (Sultan et al, 2008) is limited to the depth to the top of the first aquifer.

Therefore, **Task 1 in Year 1** is to access the ARAMCO (+/- MoWE) well and other information under suitable terms and conditions. This information will permit construction of suites of “forward models” describing the expected geophysical signature of the stacked aquifers at various locations corresponding to various depths, thicknesses, and salinity. This work does not require extremely sophisticated or powerful computing resources. It is done on a high-end PC with suitable EM “forward modeling” software. While modeling results are not 100% definitive (because they always rely in simplifications) they are useful and instructive.

Task 2 in Year 1 will be to review and comment upon the geophysical work program of the Prime Contractor.

Task 3 in Year 1, will be to begin development an initial plan for a pilot field study to take place during the field season (winter) of Year 2.

Task 4 in Year 1 will be specialized training in EM/MT of Saudi geoscientists.

YEAR 2

Task 1 – Year 2 – Review of Prime Contractor Data

In Year 2, if the Prime Contactor has acquired MT or other EM data, some or all of the data should be reviewed and commented upon by Phoenix.

It is foreseen that:

Task 4 – Year 2 – field work by Phoenix/KSU

--KSU will carry out some field work at selected location(s) during the field season of Year 2.

Task 2 -- Year 2 Additional training for Saudi experts

Before the field work, a significant amount of training of a small cadre of KSU experts is foreseen, both within Saudi Arabia and externally. This training will cover both theoretical and practical aspects, and will focus upon use of the equipment to be acquired by KSU for Year 2 field work.

Task 3 -- Year 2 Final Plan for fieldwork

Before the Field Season of Year 2, the final plan for the first fieldwork pilot study will be agreed.

Experienced logistics providers/consultants already in KSA would be the logical parties to take responsibility for organizing the field program (guided by Phoenix and KSU).

The field program will require considerable logistic support and planning for vehicles, support workers, water and fuel supply, camps, maps, etc. etc. Field work in the RAK is expected to be costly and a logistics consultant with first-hand knowledge of the area, as well as excellent planning and organization skills will be required.

Field work locations should include as many as possible of the previously mentioned ARAMCO wells, to permit calibration of the MT response to the well information.

As well, the field work may be done at locations already occupied by the Prime Contractor, if any, at that time.

YEAR 3

Task 1 – Year 3 – Analysis of data

Analysis and interpretation of data:

-- acquired by KSU

-- acquired by prime contractor.

Task 2 -- Year 3

Additional field work :

- at additional ARAMCO wells
- at locations already surveyed by Prime Contractor.

Task 3 – Year 3 – Final report

Final Report with conclusions and recommendations

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